Fragility and Recovery Models for Energy, Water, and Wastewater Systems for Seismic Regional Risk and Resilience Assessment: State-of-the-Art Review and Database

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Abstract: Fragility functions and recovery models are often used to assess lifeline systems subjected to extreme hazards. However, even though many databases for fragility and recovery models exist for essential buildings and transportation systems, fragility and recovery models for other lifelines are fragmented across the literature. This article provides a comprehensive review of the state-of-the-art seismic fragility functions and recovery models for energy (power, liquid fuel, and gas), water, and wastewater systems that can be applied in hazard risk and resiliency assessments of communities. The review focuses on fragility and recovery model parameters and summarizes the methods and validation used in developing the models. In addition, the reviewed fragility functions are compiled in an open-source database with a graphical user interface. Critical gaps in the literature are discussed to guide future research endeavors. **DOI: 10.1061/NHREFO.NHENG-1661.** *© 2023 American Society of Civil Engineers.*

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Introduction

The operability and functionality of energy, water, and wastewater lifeline systems are linked to the well-being and resilience of communities. The effectiveness of resources and services delivered through lifelines influences gross domestic product, energy independence, and economic competitiveness locally and nationally (ASCE 2013). Failure of lifelines affects postdisaster emergency response, restoration, and recovery from seismic events and increases social inequality during and following recovery (EERI 1990; Lew 1990; Todd et al. 1994; Lau et al. 1995; Schiff and Holzer 1998; NIST 1996; van de Lindt et al. 2020).

Fragility functions and recovery models have become essential to assess lifeline recovery and resilience. The development of fragility functions has a long history for nuclear power plants (Kennedy and Ravindra 1984), general US lifelines ATC-25 (ATC 1991), California lifelines ATC-13 (ATC 1985), and loss estimation for buildings, utility networks, and transportation networks (FEMA 2010). In the US, fragility function development has been undertaken by many agencies, such as the American Lifelines Alliance (ALA 2001a) for water systems; Pacific Earthquake Engineering Research (PEER) for lifelines and transportation systems; Multidisciplinary Center for Earthquake Engineering Research (MCEER) for water supply systems, electric power systems, and highway transportation systems; and FEMA for building components per FEMA P-58 (FEMA 2012). Outside the public domain, many utility providers in the US have also developed fragility functions for lifeline infrastructure, e.g., the Bureau of Environmental Service in Portland, Oregon (BES 2018), for wastewater pipes; Portland General Electric (PGE) for power transmission and distribution system (SEFT 2018); and Pacific Gas and Electric and G&E Engineering for power distribution systems (Eidinger et al. 2017) and natural gas transmission pipelines and wells (Eidinger 2020). Efforts also exist outside the US, e.g., European initiatives for the seismic risk assessment of buildings and lifelines include RISK-UE (2004), LESSLOSS (2007), SRMLIFE (2007), and SYNER-G (2013).

As a result of these efforts, several fragility functions for lifeline systems are now publicly available (FEMA 2010; van de Lindt et al. 2019; Pitilakis et al. 2014). However, unlike building and transportation lifelines, expertise for electrical, liquid fuel, natural gas, water, and wastewater lifelines spans across engineering disciplines and knowledge domains, resulting in a complex panoply of infrastructure components that needs to be clearly defined for the general user. Knowledge of the methods used to verify and validate these models is also needed to ensure that each model is appropriate for its intended application and is credible (Sargent 2011).

Based on existing knowledge, the main objective of this paper is to provide a state-of-the-art review of seismic fragility functions and recovery models developed during the last three decades (1990–2021) for energy (power, liquid fuel, and gas), water, and wastewater systems. To critically review existing fragility functions for lifelines, a comprehensive taxonomy of lifeline systems and fragility functions was compiled in a database (Alam et al. 2022a), including potential infrastructure dependencies and interdependencies. The review focuses on model parameters, methods, and validation used in developing the models. The lifeline engineering community and utility managers will find the review useful in assessing the regional seismic risk and resilience of lifeline infrastructure.

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Table 1. Taxonomy of infrastructure classes and subclasses for energy, water, and wastewater systems

Parent class	Class	Subclass	References
Energy systems	Electric power systems	Power generation plants	FEMA (2010), and Pitilakis et al. (2014)
		Transmission and distribution systems	FEMA (2010), and Pitilakis et al. (2014)
		Substations	FEMA (2010), Pitilakis et al. (2014), and IEEE 693 (IEEE 2006)
	Liquid fuel systems	Refineries	FEMA (2010), and Pitilakis et al. (2014)
		Oil pipelines	FEMA (2010), and Pitilakis et al. (2014)
		Pumping plants	FEMA (2010), and Pitilakis et al. (2014)
		Tank farms	FEMA (2010), and Pitilakis et al. (2014)
	Natural gas systems (NGS)	Storage facility	Pitilakis et al. (2014)
		Compressor stations	FEMA (2010), and Pitilakis et al. (2014)
		Gas pipelines	FEMA (2010), and Pitilakis et al. (2014)
Water and wastewater systems	Water systems (WS)	Wells	FEMA (2010), and Pitilakis et al. (2014)
		Water treatment plants	FEMA (2010), and Pitilakis et al. (2014)
		Pumping plants	FEMA (2010), and Pitilakis et al. (2014)
		Water storage tanks	FEMA (2010), Pitilakis et al. (2014), AWWA D100 (AWWA 2011), AWWA D110 (AWWA 2013), and ACI 350 (ACI 2006)
		Water pipelines	FEMA (2010), Pitilakis et al. (2014), AWWA M41 (AWWA 2008), AWWA M11 (AWWA 2017), and AWWA M23 (AWWA 2020)
	Wastewater systems (WWS)	Wastewater treatment plants	FEMA (2010), and Pitilakis et al. (2014)
		Lift or pumping stations	FEMA (2010), and Pitilakis et al. (2014)
		Wastewater pipelines and sewers	FEMA (2010), and Pitilakis et al. (2014)

Taxonomy

To define the infrastructure associated with lifelines, a taxonomy of infrastructure parent classes (energy, water, and wastewater systems) and their associated classes and subclasses was developed, as shown in Table 1. Additional information about the collection and fragility function attributes can be found in Alam et al. (2022a) and the web-based fragility function viewer application (Alam et al. 2021).

Fragility Functions

Probabilistic risk assessments often rely on the use of fragility functions to assess hazard-induced damage and loss of infrastructure, e.g., for electric power systems (NIBS 1994; Baghmisheh and Estekanchi 2019) and water and wastewater systems (Fragiadakis and Christodoulou 2014; Farahmandfar et al. 2017). A fragility function represents the conditional probability that a structure or structural component meets or exceeds a specified damage state (DS) for a given hazard intensity measure (IM). Fragility functions can also be further conditioned on a vector of infrastructure attributes, $\mathbf{X}$, and time, t, so that the effects of different infrastructure attributes and deterioration effects due to aging (e.g., age-dependent corrosion of pipes) can be considered respectively. The fragility functions can then be expressed generically as $P[\mathrm{DS}|\mathrm{IM}, \mathbf{X}, t]$, or more simply $P[\mathrm{DS}|\mathrm{IM}]$, when the infrastructure attributes and time are not explicitly considered in the fragility functions.

Different functional forms have been adopted to express fragility functions for lifelines, e.g., normal distribution for substations (Anagnos and Ostrom 2000; Anagnos 2001; Straub and Der Kiureghian 2007); lognormal distributions for power generation plants (FEMA 2010), substations (FEMA 2010; Kitayama et al. 2017), water treatment plants (FEMA 2010), and liquid fuel tank (Saha et al. 2014; Phan et al. 2016, 2017). However, the lognormal complementary cumulative distribution function (CCDF) is the most adopted functional form, which is given by

$$P[\mathrm{DS} \geq \mathrm{ds}_i|\mathrm{IM}] = \Phi\left[\frac{\ln(\mathrm{IM}) - \ln(\theta_i)}{\beta_i}\right] \qquad (1)$$

where ds_i represents damage state i with $i \in \{1, \ldots, N\}$ where N = number of damage states; θ_i and β_i are median and logarithmic standard deviation of damage state i; and $\Phi(\cdot)$ = standard normal cumulative distribution function (CDF). The parameter θ_i and β_i are often estimated using the method of moments or the maximum likelihood method (Baker 2015).

Different damage states (slight, moderate, extensive, complete, collapse), both qualitative and quantitative, have been proposed in the literature for component- and system-level fragility functions. Damage measures are used to characterize damage states for a given hazard intensity, typically defined with respect to an engineering demand parameter (EDP) representing structural response. Examples of typical damage measures for lifelines include misalignment of disconnect switches, tipping over of circuit breakers, oil leakages from transformers, and malfunction of water treatment plants. Table 2 lists probable failure mechanisms for electric power system (EPS) equipment identified through expert solicitation [(Kempner, "Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020); (Hillier and Makuakane, "Cascadia lifelines fragility functions failure mechanism discussion—Power generation plant equipment. Portland General Electric," personal communication, 2020)] and other published literature (Filiatrault et al. 1999; Anagnos 2001). Table 3 lists probable failure mechanisms of water system components gathered from the literature (e.g., O'Rourke and Liu 1999; ALA 2001a, b).

Tables 4–7 of the online repository listed in the Data Availability Statement (Alam et al. 2022b) list the prominent studies on fragility functions for the lifeline infrastructure classes and summarize relevant information related to the IMs, methods used to derive the fragility models, considered damage states, methods of verification and validation, and region for which the fragility functions were developed, and a brief description of the associated infrastructure component. In these tables, model *validation* refers to the means of establishing that the model possesses a satisfactory range of accuracy consistent for its intended application (Schlesinger et al. 1979). Model *verification* refers to the means of ensuring that the model implementation is correct.

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Table 2. Examples of probable failure mechanisms for EPS equipment

Infrastructure subclass	Equipment	Failure mechanism	References
Power generation plant	Large vertical storage vessels with formed heads	Anchorage failure, pipe connection failure, tank buckling	Hillier and Makuakane, "Cascadia lifelines fragility functions failure mechanism discussion—Power generation plant equipment. Portland General Electric," personal communication, 2020
	Large horizontal storage vessels with formed heads	Anchorage failure, pipe connection failure	
	Large vertical pumps	Anchorage failure, pipe connection failure, internal mechanical failure	
	Motor-driven pumps	Anchorage failure, pipe connection failure, internal mechanical failure	
	Large motor-operated valves	Control failure	
	Diesel generators	Anchorage failure, fuel piping failure, fuel tank failure	
	Battery racks	Anchorage failure	
	Switchgear	Anchorage failure	
Substation	Rigid bus	Supporting insulator failure, flexible strap failure with equipment or failure of tabs connected to clipment, slider failure due to insufficient tolerance	Filiatrault et al. (1999), Song et al. (2006), Kempner ("Cascadia lifelines fragility functions failure mechanism discussion— Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Flexible bus	Failure of rigid post insulator, failure of tab connected to rigid post insulator	Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Current transformer	Flexural failure at the base of insulator, tab failure at the head of current transformer, porcelain break, degradation of bottom connection of composite insulator	Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Coupling capacitor voltage transformer	Flexural failure at the base of insulator, tab failure at the head of current transformer, porcelain break, degradation of bottom connection of composite insulator, support structure damage	Anagnos (2001), Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Disconnect switches with rigid bus with rigid connection	Multiple insulator failure, misaligned switch contacts	Anagnos (2001), Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Disconnect switches with rigid bus with flexible connection	Multiple insulator failure, misaligned switch contacts	Anagnos (2001), Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Wave trap (suspended)	Pull out from wire connections	Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Wave trap (cantilevered)	Flexural failure of insulator post	Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Live tank circuit breaker	Flexural failure at the base of porcelain	Anagnos (2001), Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Dead tank circuit breaker	Bushing or bushing tab damage	Anagnos (2001), Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Transformer	Anchorage failure, radiator failure, conservator failure, surge-arrestor failure, internal failure, bushing failure (gasket extrusion, oil leakage, porcelain unit slippage, porcelain unit fracture)	Huo and Hwang (1995), Anagnos (2001), Kitayama et al. (2016), Kempner ("Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020)
	Lightning arrester	Porcelain damage	Huo and Hwang (1995), and Anagnos (2001)

Table 3. Probable failure mechanisms of water pipelines

Infrastructure subclass	Equipment	Failure mechanisms	Reference
Water storage tanks	Steel tank	Elephant foot buckling, upper shell buckling, roof system partial damage/collapse, rupture of inlet/outlet/drain/overflow pipe, rupture of bottom plate from bottom course, anchorage failure, tank support/column system failure	ALA (2001b)
	Concrete tank	Uplift/sliding of tank, wall cracking, hoop overstress, roof failure	
	Wood tank	Rupture of inlet pipe due to base sliding, wall to floor connection failure due to uplift, bars stretch causing leaks, roof damage	
Water pipelines (ground shaking)	Continuous pipes	Tensile failure, wrinkling, beam buckling, welded slip joint	O'Rourke and Liu (1999)
	Segmented pipes	Axial pull-out, crushing of bell and spigot joints, joint rotation, round flexural cracks, tensile and bending deformation of the pipe barrel	O'Rourke and Liu (1999), and ALA (2001a)
Water pipelines (ground failure—liquefaction)	Continuous and segmented	Settlement, transverse movement, axial deformation	O'Rourke and Liu (1999)
Water pipelines (ground failure—landslide)	Continuous and segmented	Perpendicular crossing: bending Oblique crossing: compression and bending Parallel crossing: tension and bending	O'Rourke and Liu (1999)

Fragility Models for Electric Power Systems

Table 4 of the online repository (Alam et al. 2022b) lists the seismic fragility functions collected for electric power systems, including subclasses for power generation plants, transmission and distribution systems, and substations. The design and assessment of electric power systems in the US has evolved on the basis of the experience gained from the damage and loss of service observed during several earthquakes on the west coast (Todd et al. 1994; Lau et al. 1995; Schiff and Holzer 1998; NIBS 1994; Eidinger et al. 2017).

For many EPS fragility functions, peak ground acceleration (PGA) is considered a sufficient IM for subclasses with shorter natural periods of vibration, such as components within power generation plants and substations. For components of transmission and distribution systems, peak ground velocity (PGV) and permanent ground deformation (PGD) have been used for ground shaking and permanent ground deformation, respectively (Kongar et al. 2014, 2017; Eidinger et al. 2017). Fragility functions have been defined on the basis of spectral acceleration (Sa) for select cases, e.g., if the fundamental frequency was highly correlated to a particular damage mode (NIBS 1994) or if the response of the component was governed by the flexibility of the supporting structure (Baghmisheh and Estekanchi 2019).

Power Generation Plants

In general, power generation plants performed well during past earthquakes, except for some heavy damage observed in power plants located in the San Francisco Bay area during the 1989 Loma Prieta earthquake (Schiff and Holzer 1998). As such, the development of fragility functions for power generation plants has received little attention except those available in NIBS (1994) and FEMA (2010).

Component-level (NIBS 1994) and system-level (FEMA 2010) heuristic fragility functions have been developed for power generation plants. A single failure damage state is considered for component fragility functions on the basis of damage factors (ratio of repair to replacement cost of the equipment) and functionality tag, which describes whether equipment will remain functional should the damage state occur (NIBS 1994). For system-level fragility functions, multiple damage states are considered on the basis of the extent of damage, availability of power, and level of service (FEMA 2010). Different sets of fragility functions are provided for anchored or unanchored components based on the level of seismic design, e.g., designed with tie-downs or tie backs or designed without seismic considerations.

Transmission and Distribution Systems

Several studies have developed empirical fragility functions for transmission and distribution systems. Multiple IMs have been used in these studies to correlate damage to hazard intensity, including modified Mercalli intensity (MMI), PGA, PGV, $Sa(T = 0.3\ \text{s})$ (period, T, of 0.3 s), PGD, and associated PGD-related metrics. Damage states have been defined by the ratio of damaged to the total feeder length (Park et al. 2006), levels of network connectivity loss (Dueñas-Osorio et al. 2007), repair rates per kilometer (Kongar et al. 2014, 2017; Eidinger et al. 2017), and failure of different lengths of cable (Kongar et al. 2014, 2017). Some repair rate relations have also accounted for the construction type, like the type of duct bank and conductor for underground distribution systems, and the age of the pole, conductor, and cross arms for overhead distribution systems (Eidinger et al. 2017).

Observations of these studies indicated that (1) $Sa(T = 0.3\ \text{s})$ is a better predictor of damage compared to PGA for the long-period response of overhead systems comprised of poles and wire (Eidinger et al. 2017); (2) in general, underground distribution systems perform better than overhead distribution systems, in which failure can occur due to the lack of slack in overhead wire and result in broken cross arms, burnt conductors, and broken attachments in overhead secondaries to adjacent structures (Eidinger et al. 2017); and (3) vulnerability of buried cables is primarily due to liquefaction rather than ground shaking and lateral spreading causes more damage than settlement (Kongar et al. 2014, 2017).

The fragility functions listed in this section were validated on the basis of empirical damage data of overhead (Park et al. 2006; Dueñas-Osorio et al. 2007; Eidinger et al. 2017) and underground (Kongar et al. 2014, 2017; Eidinger et al. 2017) distribution networks. Although these empirical studies were based on historic damage data and, hence, validated against observed damage states, none of these studies split the damage data by using part of the data to build the model and the remaining data to evaluate the model—a common approach when validating with historical data (Sargent 2011). Park et al. (2006) provided validation by comparing fragility functions developed using data from the 2001 Nisqually and the 1995 Kobe earthquakes. To classify the liquefaction zones used for the fragility development, Kongar et al. (2017) used a LiDAR

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data set, with qualitative data set of liquefaction observation based on postearthquake reconnaissance and aerial photography.

Substations

Fragility functions for substations can account for varying configurations of the components, including (1) stand-alone configurations (Huo and Hwang 1995; Vanzi 1996; Anagnos and Ostrom 2000; Zareei et al. 2016; Ang et al. 1996; Vanzi 2000; Shinozuka et al. 2007); (2) connected configurations accounting for the dynamic interaction of components (Siraj et al. 2015; Baghmisheh and Estekanchi 2019); (3) open-gate and closed-gate operation configurations for the disconnect switch (Wen et al. 2019); (4) base isolation of the transformer (Kitayama et al. 2017), capacitor voltage transformers and lightning arresters (Mohammadi and Mosaffa 2018), or capacitor voltage transformers (Cheng et al. 2018); (5) consideration of anchorage for the transformer; and (6) statistical dependence of the system components (Straub and Der Kiureghian 2007). Fig. 1 shows fragility functions for substation equipment from these studies. Due to higher damping from dynamic interactions and restricted out-of-plane movement of the components, the advantageous effect of connected configurations [Fig. 1(a)] for current transformers and surge arresters and closed-gate operation configuration for disconnect switches [Fig. 1(b)] is evident. Figs. 1(c and d) illustrate the decreased vulnerability of base-isolated and anchored transformers due to reduced seismic response with base isolation and strengthening of vulnerable connections with anchorage.

These studies suggest that (1) although multiple failure modes are probable in substation equipment (Anagnos 2001; Kempner, "Cascadia lifelines fragility functions failure mechanism discussion—Substation equipment. Bonneville Power Administration," personal communication, 2020), many of these failures are governed by tensile failure/cracking of the brittle porcelain component (Zareei et al. 2016; Zareei et al. 2017; Mohammadi and Mosaffa 2018; Baghmisheh and Estekanchi 2019); (2) retrofitting through anchorage (Hwang and Chou 1998) or base isolation substantially improves equipment seismic performance (Kitayama et al. 2017; Cheng et al. 2018; Mohammadi and Mosaffa 2018); (3) neglecting statistical dependence among the system components can lead to significant overestimation of the system fragility (Straub and Der Kiureghian 2007); and (4) considering dynamic interaction between the connected components has significant effects on fragility, which varies depending on the component's dynamic characteristics (Mohammadi and Mosaffa 2018; Baghmisheh and Estekanchi 2019).

Many of these fragility functions were validated against empirical data (Anagnos and Ostrom 2000; Anagnos 2001; Siraj et al. 2015; Zareei et al. 2016; Kitayama et al. 2016; Zareei et al. 2017) or experimental results, e.g., material mechanical tests like static pull test (Wen et al. 2019), pseudodynamic tests (Paolacci et al. 2014), or shake-table tests (Vanzi 1996; Cheng et al. 2018; Mohammadpour and Hosseini 2017; Baghmisheh and Estekanchi 2019; Wen et al. 2019).

Fragility Models for Liquid Fuel Systems

Table 5 of the online repository (Alam et al. 2022b) lists the seismic fragility functions collected for liquid fuel systems (LFS), including subclasses for refineries, oil pipelines and pumping plants, and tank farms and liquid fuel tanks. In past earthquakes, liquid fuel systems suffered limited damage because these facilities (e.g., refinery, pumping stations, oil pipelines) are generally built per seismic codes, with ductile materials and anchored components that tend to exhibit resistance to ground shaking (SYNER-G 2013). Strong shaking during the 1994 Northridge earthquake did result in

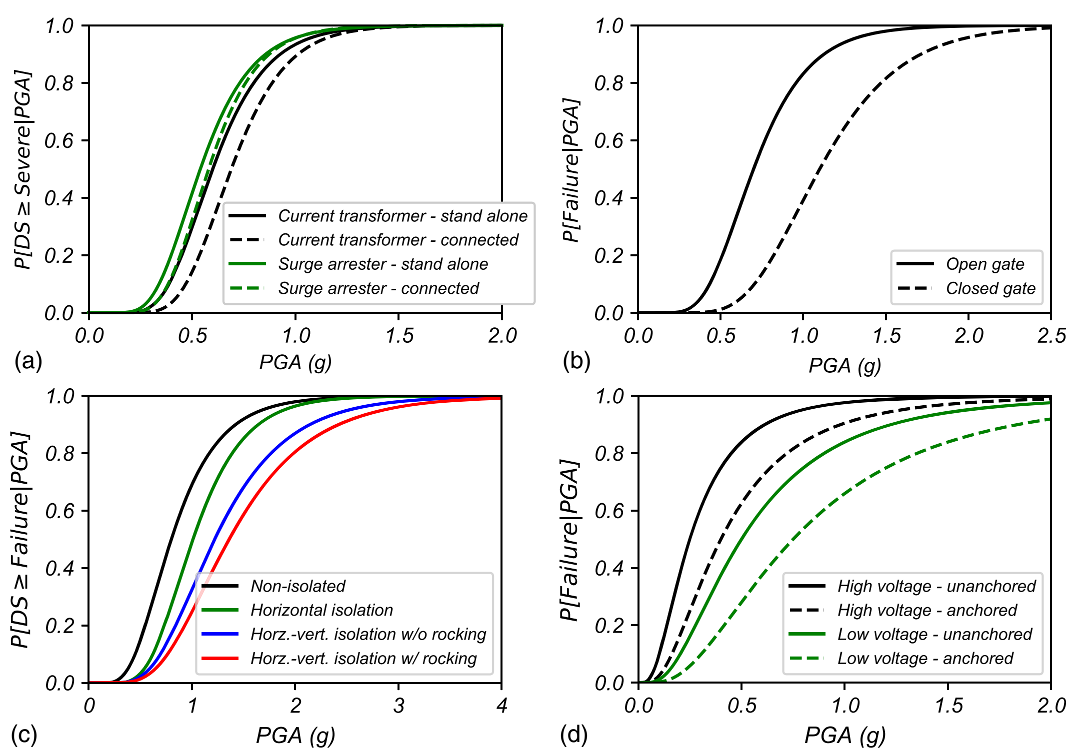

Fig. 1. Example of substation equipment fragility functions for: (a) current transformers and surge arresters in stand-alone (solid line) and connected (dashed) configurations (data from Baghmisheh and Estekanchi 2019); (b) 230-kV disconnect switches with open gate (solid line) and closed gate (dashed line) operation configurations (data from Wen et al. 2019); (c) nonisolated and base-isolated transformers (data from Kitayama et al. 2017); and (d) low- and high-voltage transformers with (dashed lines) and without (solid lines) anchorage (data from NIBS 1994).

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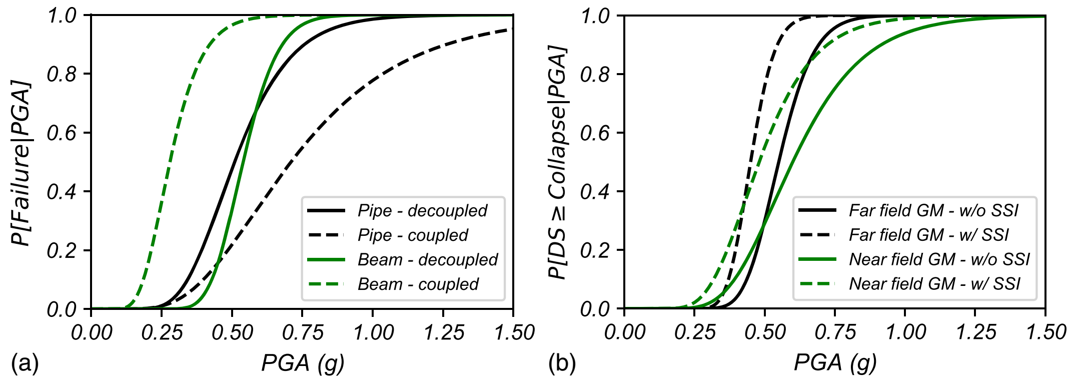

Fig. 2. Example of fragility functions of refinery pipe rack–piping system: (a) component fragility for pipes and beam considering decoupled (solid line) and coupled (dashed line) case (data from Farhan and Bousias 2020); and (b) pipe fragility functions for decoupled configuration with (dashed line) and without (solid line) consideration of soil-structure interaction (data from Di Sarno and Karagiannakis 2020).

cracked welds at several locations along a 250-mm pipeline transporting crude oil from the San Joaquin valley, spilling oil along the Santa Clara River (Todd et al. 1994).

Refineries

Component-level, e.g., elbows, bolted flange joints, pipe racks (Caprinozzi et al. 2017; Bursi et al. 2018; Di Sarno and Karagiannakis 2019b; Hosseini et al. 2020; Abbiati et al. 2021), and system-level (Farhan and Bousias 2020; Di Sarno and Karagiannakis 2020) fragility functions have been developed for piping systems within oil refineries. Analytical fragility functions have been based on three-dimensional nonlinear FEM simulations of pipe rack and piping systems considering shear and flexural failure of the pipe rack and tensile and buckling failures of the pipes (Caprinozzi et al. 2017; Bursi et al. 2018; Di Sarno and Karagiannakis 2020) and soil-structure interaction (SSI) of pipe rack support (Di Sarno and Karagiannakis 2019b, 2020). Some have also used surrogate modeling and hybrid simulation techniques (Abbiati et al. 2021). Fig. 2(a) shows component fragility functions of a pipe rack system, in which it is evident that dynamic interaction of components (decoupled versus coupled case) can significantly affect the component fragility; this effect is component dependent (Farhan and Bousias 2020). From Fig. 2(b), incorporating SSI in the model increases the vulnerability of the pipes in the refinery; the extent of increase in vulnerability depends on the ground motion source (near field versus far field).

Dynamic interaction between the pipe rack and piping (Farhan and Bousias 2020; Di Sarno and Karagiannakis 2019b), SSI (Di Sarno and Karagiannakis 2019b, 2020), and vector-valued intensity measures (Hosseini et al. 2020) have been identified as important parameters when assessing the vulnerability of oil refinery piping systems. Results have suggested that (1) consideration of coupling between the pipe rack and piping increases the vulnerability of the pipe rack–piping system by changing the piping system boundary conditions (Farhan and Bousias 2020; Di Sarno and Karagiannakis 2020); (2) consideration of SSI increases the vulnerability of the system (Di Sarno and Karagiannakis 2019b, 2020); and (3) vector-valued IMs comprising of {PGA, PGV} provide more reliable vulnerability estimates of the piping system compared to scalar PGA-based IMs (Hosseini et al. 2020).

Limited verification and validation information is available for many of these fragility functions, except for Abbiati et al. (2021) in which the response history of elbow hoop strains was validated against hybrid simulation test results. In some of these studies, damage state thresholds were defined on the basis of experimental results and recommendations in codes and standards (Caprinozzi et al. 2017; Bursi et al. 2018).

Oil Pipelines and Pumping Plants

To date, a limited number of fragility functions have been developed for oil pipelines and pumping plants. FEMA (2010) provides heuristic fragility functions (repairs/km) for brittle and ductile oil pipelines as a function of PGV and PGD. Mild steel pipelines with submerged arc welded joints were classified as ductile pipes, whereas older gas welded steel pipelines were classified as brittle pipes. For pumping plants, fragility functions have been provided as a function of PGA with distinctions for anchored and unanchored components (FEMA 2010).

Tank Farms and Liquid Fuel Tanks

Several empirical (Salzano et al. 2003; Fabbrocino et al. 2005; D'Amico and Buratti 2019) and analytical (Iervolino et al. 2004; Razzaghi and Eshghi 2008; Saha et al. 2014; Paolacci et al. 2015; Phan et al. 2016, 2017; Cortes and Prinz 2017; Joorabi and Razzaghi 2019; Phan et al. 2019; Wang et al. 2021) seismic fragility functions have been developed for liquid fuel tanks.

Empirical fragility functions have been developed based on tank damage databases (Cooper 1997) and other publicly available articles and reports (e.g., Haroun 1983; Hatayama 2008; Yazici and Cili 2008). In empirical fragility functions, the effects of different geometric and material characteristics of the tanks (e.g., slenderness of the tanks, fill levels, seismic anchorage) have been investigated using either Probit (Salzano et al. 2003; Fabbrocino et al. 2005) or Bayesian (D'Amico and Buratti 2019) regression analyses with historic damage data. Limit states in empirical fragility functions have been typically defined on the basis of loss of contents, e.g., negligible, slight, or rapid loss of the tank's contents (Salzano et al. 2003; Fabbrocino et al. 2005). More recent empirical fragility functions have considered both structural damage (damage to the tank wall, bottom plate, roof, or piping system) and leakage of the tank's contents (D'Amico and Buratti 2019).

In analytical fragility functions, component- and system-level fragility functions have been developed by simulating the different failure modes of tanks, e.g., plastic deformation of the shell and roof (Iervolino et al. 2004; Razzaghi and Eshghi 2008; Paolacci et al. 2015; Phan et al. 2016; Cortes and Prinz 2017; Phan et al. 2017; Wang et al. 2021). Models have ranged from simple surrogate models of the tanks with linear springs and lumped plasticity models (Bakalis et al. 2015; Paolacci et al. 2015; Phan et al. 2016, 2017) to more advanced three-dimensional (3D) FEMs that

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accounts for fluid-structure interaction (Joorabi and Razzaghi 2019; Phan et al. 2019, 2020; Wang et al. 2021). Many of these studies investigated the effects of anchorage, tank slenderness, and fill level on seismic fragility (Iervolino et al. 2004; Razzaghi and Eshghi 2008). Some recent studies have also investigated other less-explored aspects like base isolation (Saha et al. 2014), ultra-low-cycle fatigue of the shell-to-base connections (Cortes and Prinz 2017), shell corrosion (Joorabi and Razzaghi 2019), and the effects of efficiency and sufficiency of the selected IMs (Phan et al. 2017) and analysis method (Paolacci et al. 2015; Phan et al. 2016).

Based on this literature, common observations have included the following: (1) slender tanks are more vulnerable than squat tanks (Salzano et al. 2003; Fabbrocino et al. 2005; Razzaghi and Eshghi 2008; Cortes and Prinz 2017; D'Amico and Buratti 2019); (2) anchored tanks perform better than unanchored tanks (D'Amico and Buratti 2019); (3) seismic vulnerability increases as the fill level increases (Iervolino et al. 2004; Razzaghi and Eshghi 2008; Phan et al. 2019; D'Amico and Buratti 2019); (4) corrosion and base isolation considerably increases and decreases the seismic vulnerability of tanks, respectively (Joorabi and Razzaghi 2019; Saha et al. 2014); and (5) deterministic fill levels assumed for the tanks could lead to biased fragility estimates (Phan et al. 2019).

Empirical fragility functions (Salzano et al. 2003; Fabbrocino et al. 2005; D'Amico and Buratti 2019) have been developed on the basis of historic damage data of atmospheric tanks collected from past earthquakes. The cited literature did not perform additional validation when developing these empirical fragility functions. Analytical fragility functions have been validated via comparisons of (1) FEMA (2010) against other empirical fragility functions (Razzaghi and Eshghi 2008); (2) two-dimensional FEM response against seismic design standards and detailed 3D FEM response (Cortes and Prinz 2017); (3) FEM's modal characteristics against ambient vibration test results of tanks with different fill levels (Joorabi and Razzaghi 2019); and (4) FEM's hydrodynamic pressure, sloshing wave height, and base uplift displacement against shake-table test results (Phan et al. 2019).

Fragility Models for Natural Gas Systems

Table 6 of the online repository (Alam et al. 2022b) lists the seismic fragility functions collected for natural gas (NG) systems, including subclasses for storage facilities, compressor stations, and gas pipelines. Like liquid fuel systems, natural gas systems (compressor stations, gas pipelines) have performed well in past earthquakes. Gas lines designed to code and made of ductile materials, such as steel, PVC, and medium- or high-density polyethylene (MDPE or HDPE) have generally performed well except for pipelines crossing faults, which require additional measures and special design considerations (Lau et al. 1995; Giovinazzi et al. 2011).

Storage Facility

Natural gas storage facilities are either underground or surface storage facilities. Subsurface facilities are usually located 100 m below the surface and are natural geological reservoirs, such as depleted oil or gas fields or salt caverns. These facilities are used to balance seasonal variations in gas supply and demands, i.e., between the heating and nonheating periods). Most existing natural gas storage in the United States are in depleted natural gas or oil fields that are close to consumption centers. Above ground, natural gas is usually stored in its liquefied natural gas (LNG) state in specific LNG tanks.

At present, fragility functions for subsurface storage facilities are nonexistent and very few seismic fragility functions have been developed for LNG tanks (Lee et al. 2013; Kim et al. 2019). Although documentation on the performance of natural gas storage facilities during past earthquakes is scarce, the risk to natural gas storage facilities can be inferred from the performance of liquid storage facilities during past earthquakes [e.g., 1999 Kocaeli earthquake (Sezen and Whittaker 2006; Girgin 2011), 1999 Chi-Chi earthquake (Chen et al. 2002), and Wenchuan earthquake (Krausmann et al. 2010)]. Natural gas storage facilities may experience similar risks during ground-shaking and fire-following earthquakes due to the inherent vulnerability of these types of facilities, e.g., non-seismically designed RC supporting structures in LNG plants (Kothari et al. 2017; Di Sarno and Karagiannakis 2019a) or proximity of some of these facilities to riverbanks where the soil is vulnerable to liquefaction and lateral spreading, as in the critical energy infrastructure (CEI) hub of Oregon on the western bank of the lower Willamette River in northwest Portland (OSSPAC 2013).

Compressor Stations

FEMA (2010) provides fragility functions for compressor stations that are identical with those of oil pumping plants. For European applications, heuristic fragility functions for compressor stations with anchored components housed in seismically designed low-rise RC buildings have been proposed in SRMLIFE (2007) for Greece. The use of the FEMA (2010) fragility functions has been suggested for other countries.

Gas Pipelines

Empirical fragility functions based on an extensive database of NG pipelines damage in past earthquakes have been proposed in terms of probability of damage, e.g., for continuous pipes (Lanzano et al. 2013, 2014), segmented pipes (Lanzano et al. 2014), and strain limits (Eidinger 2020). Eidinger (2020) compiled a large database of pipeline damage from 29 earthquakes in California (from 1906 to 2019) and other earthquakes in Japan, New Zealand, and Alaska. In most large earthquakes in California, the number of repairs to natural gas pipelines have been estimated between 0% and 3% for transmission systems, 3% and 30% for distribution systems, and 60% and 90% for service laterals and riser/meter sets.

Most available seismic fragility functions for NG pipelines have been based on empirical fragility functions for water pipelines (Tsinidis et al. 2019). Although there are many similarities between natural gas pipelines and water pipelines, there are also many differences in various aspects including the pipe material, welded joints, and operating pressure (Eidinger 2020). An enhanced version of the ALA (2001a) relationship for water pipelines has been proposed for NG pipelines in terms of *repair rate per unit length* and additional factors to account for corrosion, pipe diameter, quality of welds, ground shaking duration, and pipe orientation with respect to permanent ground deformation. Discrete probability estimates of a pipe being in different damage states have also been proposed on the basis of tensile and compressive strain limits for multiple failure modes (elastic, yielding, and ultimate strain) of the pipe barrel.

A few recent studies have employed numerical methods to develop analytical fragility functions. These studies modeled different aspects of buried pipe behavior, including material and geometric uncertainty, e.g., impacts of pipe diameter to thickness ratio (D/t), burial depth to diameter (H/D), steel grade (Jahangiri and Shakib 2018; Tsinidis et al. 2020), and straight versus bending pipes (Lee et al. 2016); uncertainty in soil characteristics like backfill compaction level, pipe-soil interface friction, and cohesion (Yoon et al. 2019; Tsinidis et al. 2020); presence of anchor blocks (Ashrafi et al. 2019); time-varying response of the pipe (Liu et al. 2021); and efficiency and sufficiency of the selected IMs (Shakib and Jahangiri 2016). Fig. 3 shows examples of fragility functions for natural gas pipelines from these studies, in which vulnerability of the pipelines increases with increasing burial depth [Fig. 3(a)] and trench soil stiffness [Fig. 3(b)] due to increased seismic demand on

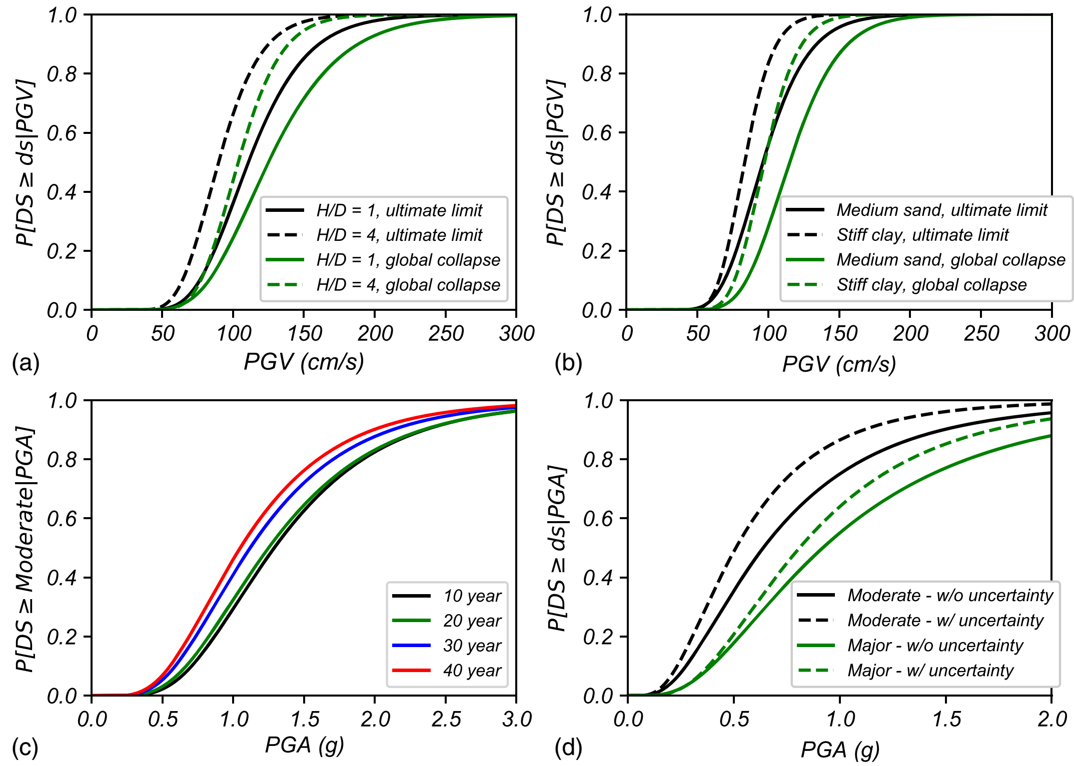

Fig. 3. Example of fragility functions for natural gas pipelines: (a) effect of burial depth (data from Jahangiri and Shakib 2018); (b) effect of trench soil properties (data from Jahangiri and Shakib 2018); (c) time-dependent fragility function of pipes susceptible to corrosion in alkaline soil (data from Liu et al. 2021); and (d) effect of considering soil parameter uncertainty on pipe fragility (data from Yoon et al. 2019).

the pipes (Jahangiri and Shakib 2018). Fig. 3(c) illustrates the deteriorating impact of corrosion on the seismic fragility functions of pipes in alkaline soil environments for various times over the service life of the pipe (Liu et al. 2021). Fig. 3(d) shows the effect of considering soil properties on uncertainty for the seismic fragility of pipelines (Yoon et al. 2019).

Important findings from these studies have indicated that (1) the fragility of pipes increases with increasing H/D ratio and increasing shear modulus of the soil and decreases with increasing steel grade (Jahangiri and Shakib 2018); (2) considering soil uncertainty increases the vulnerability of the pipe (Yoon et al. 2019); (3) pipes buried in well-compacted stiff soil with a high friction coefficient are more vulnerable than pipes embedded in a medium-compacted surficial layer with a moderate friction coefficient (Tsinidis et al. 2020); and (4) the vulnerability of pipes increases with increasing service life and decreasing pipe diameter (Liu et al. 2021).

For validation, empirical fragility functions have been developed using historic pipe damage data collected from different earthquakes (Lanzano et al. 2013, 2014; Eidinger 2020). Several verification and validation techniques have been employed in the development of analytical fragility functions for gas pipes, such as comparisons of (1) soil-spring models used to model pipe-soil interaction against the ALA (2001a) guidelines (Lee et al. 2016; Ashrafi et al. 2019); and (2) stress-strain behavior of 3D soil-pipe interaction models against equivalent infinitely long 3D continuum models subjected to same kinematic loading condition (Tsinidis et al. 2020).

Fragility Models for Water and Wastewater Systems

Table 7 of the online repository (Alam et al. 2022b) lists the seismic fragility functions collected for water and wastewater systems, including subclasses for water treatment plants and pumping plants, water storage tanks, water pipelines, wastewater treatment plants and lift stations, and wastewater pipelines. Experience from past earthquakes shows that seismic damage to water system elements can cause extensive direct and indirect economic losses with serious environmental and societal impact due to the spatial extent of such systems over large geographic areas with different geotechnical and geomorphological conditions, e.g., 1989 Loma Prieta (Eidinger 1998), 1994 Northridge (Todd et al. 1994; Lau et al. 1995; O'Rourke and Jeon 1999; Schiff and Holzer 1998), and 2010 Maule (Eidinger 2012).

Water Treatment Plants and Pumping Plants

In the US, heuristic fragility functions in terms of PGA have been proposed for water treatment plants and pumping plants on the basis of the damage data from past earthquakes (FEMA 2010). Distinctions were made between water systems with unanchored and anchored components. Damage states were defined on the basis of qualitative descriptions of the extent of damage and time to restore function. In European applications, fragility functions developed in SRMLIFE (2007) for water treatment plants and pumping stations have been proposed by Pitilakis et al. (2014). Like FEMA (2010), distinctions were made for unanchored and anchored components. Damage states were based on qualitative descriptions of the extent of damage and the associated restoration costs and loss of serviceability.

Water Storage Tanks

Fragility functions for water storage tanks can be broadly classified as heuristic (FEMA 2010; Pitilakis et al. 2014), empirical (O'Rourke and So 2000; ALA 2001a; Berahman and Behnamfar 2007), or analytical (Buratti and Tavano 2014; Saha et al. 2016;

Tsipianitis and Tsompanakis 2018). Heuristic fragility functions for tanks of concrete, steel, and wood with different configurations (e.g., on-ground, above-ground, buried) and seismic components (anchored versus unanchored) have been provided in FEMA (2010) for damage states on the basis of the extent of damage and loss of contents.

Empirical fragility functions have been developed on the basis of tank damage data gathered from past earthquakes and consideration of important physical aspects of the tank, e.g., tank slenderness (O'Rourke and So 2000); fill level (O'Rourke and So 2000; ALA 2001a); anchorage (ALA 2001a); and uncertainties in the seismic demands, measurement errors, and the finite sample size of the database (Berahman and Behnamfar 2007).

Analytical models have been developed on the basis of numerical FEM simulations or surrogate models considering fluid-structure interaction and the relevant uncertainty in tank material, tank geometry, and ground motion. Analytical fragility functions have addressed different failure modes of the tanks, e.g., failure of anchor/weld at the tank wall and base connection, breakage of the inlet-outlet pipe, roof damage, elephant foot buckling of wall, yielding of the hoop, and base uplift (ALA 2001a); multiple IMs like *Sa* and PGD (ALA 2001a) or PGA, PGV, PGD, and *Sa* (Buratti and Tavano 2014); and the effects of base isolation (Saha et al. 2016; Tsipianitis and Tsompanakis 2018).

Results of these studies have suggested that (1) tank slenderness and the relative amount of stored content (percent full) significantly affect tank seismic performance; (2) PGD is the most efficient and sufficient IM compared to PGA, *Sa*, and PGV when maximum radial displacement is used as the EDP for anchored steel tanks (Buratti and Tavano 2014); and (3) isolator characteristics (isolator period of vibration, damping, yield strength, and yield displacement) and configuration affect the fragility of base-isolated tanks (Saha et al. 2016; Tsipianitis and Tsompanakis 2018).

Empirical fragility functions for water tanks have been developed using tank damage databases of observed damage states after earthquakes (Cooper 1997; ALA 2001a). Various validation techniques have been employed for analytical fragility functions, including the use of validated modeling approaches of tanks from the published literature (Buratti and Tavano 2014; Saha et al. 2016), comparing the tank's impulsive fundamental period against design codes (Tsipianitis and Tsompanakis 2018), and comparing FEM's response against shake-table test results of unanchored tanks (Phan et al. 2020).

Water Pipelines

Postearthquake field observations have demonstrated that seismically induced permanent ground deformations due to landslide, liquefaction-induced settlement and lateral spreading, and fault movements may induce extensive damage to buried pipelines (O'Rourke and Liu 1999). Seismic wave propagation–induced transient deformations have also caused damage to buried pipelines, although to a lesser extent (O'Rourke 2009). Several factors including the pipe size, material, joint type, coating, trench-backfill conditions, and age may affect seismic vulnerability (Eidinger 1998).

A large number of empirical fragility relations have been proposed over the last 30 years for buried pipelines (O'Rourke and Ayala 1993; Eidinger 1998; O'Rourke and Jeon 1999; ALA 2001a; O'Rourke and Deyoe 2004; Jeon and O'Rourke 2005; FEMA 2010; Farahmandfar et al. 2017; Bellagamba et al. 2019). Many of these relations provide linear or power law equations between the pipeline repair rate, *RR* (i.e., number of pipe repairs per unit of pipeline length required after an earthquake event), and a selected seismic IM (ALA 2001a):

$$RR = \begin{cases} a\mathrm{IM} \\ a\mathrm{IM}^b \end{cases} \tag{2}$$

where parameters a and b are defined on the basis of the regression analysis of pipe damage data. Strictly speaking, Eq. (2) does not represent the classic definition of fragility function, which involves probabilistic estimation of exceeding a damage state given a hazard intensity. However, in the literature, the power law form in Eq. (2) has been universally used to describe the fragility of pipelines for potable water, wastewater, natural gas, and liquid fuel systems. Other terms have been used to describe the number of pipe repairs per unit length of pipe, such as *damage function*, *damage rate*, *damage ratio*, and *failure rate* (Piccinelli and Krausmann 2013). Assuming that the *RR* follows Poisson probability distribution (e.g., ALA 2001a; Fragiadakis and Christodoulou 2014), the probability of at least one failure on a given pipe segment of length L can then be estimated as

$$P_f = 1 - e^{RR \times L} \tag{3}$$

To account for various parameters on the seismic vulnerability of buried pipelines, different modification factors have been introduced to the fragility relationships in Eq. (2), such as multiplication factors representing material type, soil type, pipe diameter, and joint type (Eidinger 1998; ALA 2001a); previous failure history (Farahmandfar et al. 2017); and time-dependent pipe corrosion (Mazumder et al. 2019). Fig. 4 shows water pipelines fragility functions for different seismic hazards and pipe attributes. The ALA (2001a) fragility functions for pipes subject to ground shaking and ground deformation IMs are shown in Figs. 4(a and b), respectively. These figures illustrate the larger vulnerability of pipes to landslide, liquefaction, and lateral spreading–induced permanent ground deformation IM compared to ground shaking IM. Scatter also exists in the empirical fragility fitting data, which is not represented in the median fragility functions commonly used in practice. Figs. 4(c and d) show the deteriorating effects of pipe failure history (Farahmandfar et al. 2017) and time-dependent corrosion (Mazumder et al. 2019) on pipe fragility with ground shaking hazard.

For ground shaking hazards, empirical damage ratio relationships (repairs/km) have been developed as a function of PGV (O'Rourke and Ayala 1993; FEMA 2010; Eidinger 1998), pipe diameter (D), and scaled velocity [defined as the ratio of PGV to pipe diameter (PGV/D)] (O'Rourke and Jeon 1999). For landslide, liquefaction, or lateral spreading–induced ground deformation, PGD has been widely used as an IM (Eidinger 1998; ALA 2001a; FEMA 2010). Other IMs, such as peak ground strain (O'Rourke and Deyoe 2004; O'Rourke 2009) and composite IMs like $\mathrm{PGV}^2/\mathrm{PGA}$ (Pineda-Porras and Najafi 2010) have also been used.

Compared to the substantial number of existing empirical fragility functions, analytical fragility functions for water pipelines are limited. Using classic fragility definition, Jacobson and Grigoriu (2008) developed parameterized fragility functions of continuous and segmented water pipeline for ground shaking and ground deformation hazards as a function of earthquake magnitude, source-to-site distance, and soil characteristics considering axial strain of pipes as damage state EDP.

Results of these studies have revealed that (1) pipe vulnerability depends more on the subsoil conditions and corrosion in the pipes than on the pipe material (O'Rourke and Ayala 1993); (2) ductile pipelines [e.g., PVC, modified polyvinyl chloride (MPVC)] perform better than brittle pipes (CI, AC, WI) (FEMA 2010; O'Rourke et al. 2012); and (3) pipes that operate at higher pressures

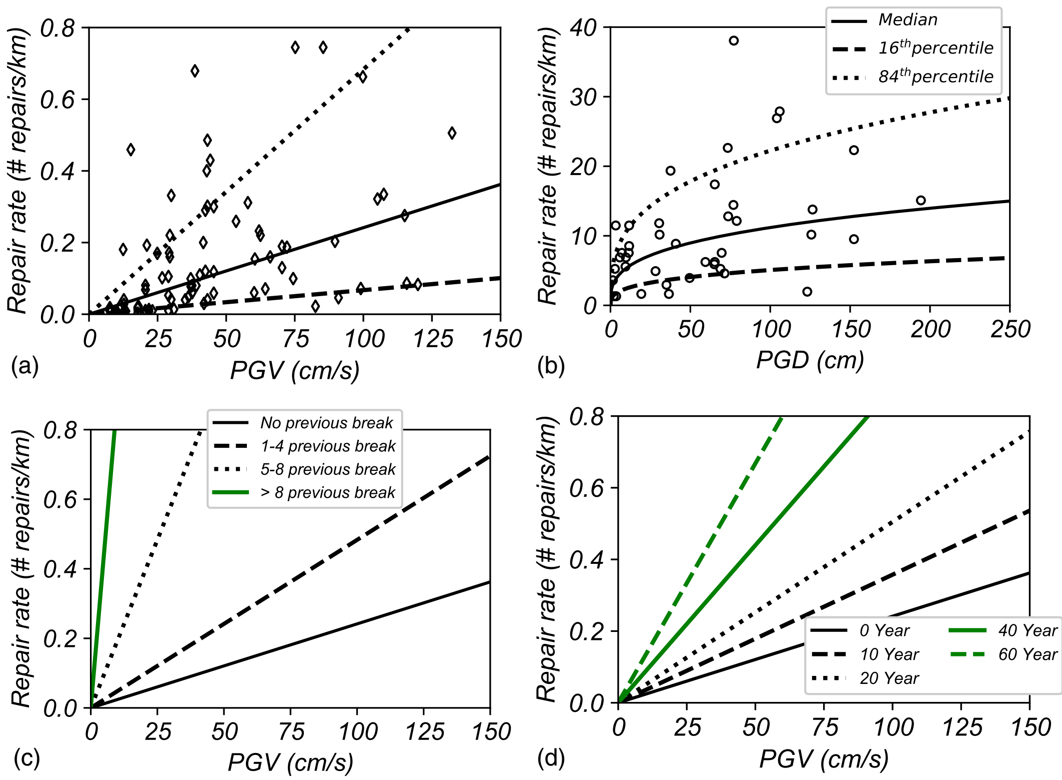

Fig. 4. (a) Example of fragility functions for water pipelines for ground shaking hazard (solid, dashed, dotted line represent the median, 16th and 84th percentile fragility, respectively); and (b) for ground deformation hazard (data from ALA 2001). The diamond and circle in these figures represent pipe repair data gathered in different earthquakes used for fragility fitting; (c) water pipe fragility accounting for pipe damage history (data from Farahmandfar et al. 2017); and (d) time-dependent fragility functions accounting for corrosion of pipes over service life (data from Mazumder et al. 2019).

are more vulnerable than those operating at comparatively lower pressure (Jeon and O'Rourke 2005).

Almost all fragility functions for water pipeline have been based on pipe repair data collected by different utility companies in the aftermath of earthquakes. Limited validation has been performed in these studies, with the notable exception of one recent study by Bellagamba et al. (2019) that used pipeline damage data from the Christchurch water distribution systems from 2010–2011 Canterbury, New Zealand, earthquake sequence. Part of the data was used for model fitting and the rest of the data was used for K-fold cross validation to minimize model error and to avoid overfitting. Analytical water pipeline fragilities by O'Rourke (2009) were also compared with other empirical repair rate relationships as part of the validation process.

Wastewater Treatment Plants and Lift Stations

Fragility functions for wastewater treatment plants and lift stations are limited in the literature. FEMA (2010) provides heuristic fragility functions for small, medium, and large wastewater treatment plants for ground shaking hazards. For ground deformation hazards, fragility functions for wastewater treatment plants are often assumed to be similar to those of water treatment plants. Fragility functions for lift stations are assumed to be similar to those of water pumping plants.

Wastewater Pipelines

Compared to the considerable number of fragility functions available for water pipelines, only a few fragility functions exist for wastewater pipelines. Due to the availability of fragility functions for only a limited number of pipe types and material categories, it is common practice to use potable-water pipe fragility functions to estimate the vulnerability of wastewater systems (e.g., ALA 2001a; FEMA 2010; Makhoul et al. 2020), potentially underestimating the physical damage to wastewater gravity pipelines, as observed in past earthquakes (Liu et al. 2015).

The increasing need for fragility functions for materials unique to wastewater systems (e.g., earthen wire, tile, vitrified clay) has led to the development of several empirical fragility functions in terms of the damage ratio [e.g., number of faults per kilometer (Shoji et al. 2011; Liu et al. 2015; Baris et al. 2020), functional disruption length per kilometer (Shoji et al. 2011; Nagata et al. 2011), or probability of damage (Baris et al. 2020)] or repair rate [e.g., number of repairs per kilometer (Liu et al. 2015)] with respect to IMs such as PGV, seismic intensity, and liquefaction potential index (LPI).

Models for Restoration and Recovery

Compared to fragility functions, which are physics-based or first principle–based, restoration and recovery models need to be empirically defined or learned from the data based on some combination of modeling, experience, and expert judgment. Restoration and recovery models represent a complex/agglomerate system of systems spanning physical, economic, organizational, technological dimensions (NIST CRPG 2016). Importantly, there are inherent difficulties related to the quantification of the restoration process, such as subjectivity, human factors, amount and availability of input data, and large uncertainties related to postevent available resources (Kammouh et al. 2018; Sharma and Chen 2020; De Iuliis et al. 2021a, b). Some notable studies have sought to address these issues

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(FEMA 2010; Davis 2014; Cimellaro et al. 2015; Porter 2016; Zorn and Shamseldin 2015, 2017; Mazumder et al. 2019, 2020; De Iuliis et al. 2021a, b). Recently, with the growing popularity of resilience-based design and assessment of infrastructure, more versatile restoration models have become available (Davis 2014; Cimellaro et al. 2015; Zorn and Shamseldin 2017; Mazumder et al. 2020). Table 8 of the online repository (Alam et al. 2022b) lists the restoration and recovery models collected for different lifelines.

On the basis of expert opinion survey data ATC-13 (ATC 1985), FEMA (2010) developed continuous restoration functions for the components of electric power systems, liquid fuel systems, natural gas systems, and water and wastewater systems. In FEMA (2010), models were defined by normal CDF and discrete restoration functions in terms of achieving restoration probabilities within specific days, e.g., 1 day, 3 days, 7 days, 30 days, and 90 days after the event. Kammouh et al. (2018) and De Iuliis et al. (2021a) have also developed restoration functions for water, gas, power, and telecommunication networks on the basis of a database collected from the literature on the restoration of different lifelines damaged in earthquakes using fuzzy logic and Bayesian network analysis. Most of the restoration and recovery models cited in literature have been on the basis of field data (e.g., natural gas systems: Cimellaro et al. 2015; water systems: Davis et al. 2012; Davis 2014) or simulations (e.g., water systems: Tabucchi et al. 2010; Porter 2016; Porter et al. 2017). However, several researchers have proposed analytical recovery models involving different functional forms depending on the level of preparedness of the given utilities, e.g., linear, trigonometric, and exponential (Cimellaro et al. 2010). Linear recovery has been assumed for averagely prepared utilities or when detailed information is lacking (Mazumder et al. 2019), trigonometric recovery has been assumed for poorly prepared utilities, and exponential recovery pattern has been assumed for utilities that are well prepared for a disaster (Porter 2016; Porter et al. 2017).

Restoration measures vary across lifelines in the literature and have included (1) the time required to recover partial or full system functionality for different damage states (FEMA 2010); (2) the probability of recovery time to restore full service (Kammouh et al. 2018; De Iuliis et al. 2021a; Gol et al. 2019); (3) the time required to recover partial or full system serviceability (Tabucchi et al. 2010; Choi et al. 2018); (4) the time required to restore service to a percentage of customers, e.g., 90% customers (T90), 98% customers (T98) (Çağnan et al. 2006; Tabucchi et al. 2010; Kang and Lansey 2013); (5) component- and system-level repair of pipes over time, e.g., percentage (%) of repairs completed and services available over time (Porter 2016; Porter et al. 2017), system repair rate (%) over time (Liu et al. 2017), or system repair probability over time (Mazumder et al. 2019); (6) system recovery effectiveness (Mazumder et al. 2020); and (7) the percentage of several service categories restored over time (Davis et al. 2012; Davis 2014; Zorn and Shamseldin 2017). Some studies have even used composite restoration measures, e.g., defined as a combination of flow rate and pipe length in service (Cimellaro et al. 2015), or system recovery effectiveness, e.g., defined as a combination of topological network efficiency, system hydraulic availability, and hydraulic resilience measures (Mazumder et al. 2020).

Most of these recovery models have utilized some form of validation during model development. For example, using (1) theoretical distributions fit to empirical recovery data of multiple lifelines, e.g., using Kolmogorov-Smirnov (K-S) and the chi-square goodness-of-fit tests (Kammouh et al. 2018; De Iuliis et al. 2021a); (2) statistical models fit to empirical restoration data using multiple validation data sets, e.g., random sampling and out-of-sample validation data sets for wastewater systems (Liu et al. 2017); (3) cross-validation of the restoration process of utility companies and estimates from analytical models, e.g., for water utilities (Porter 2016; Porter et al. 2017); (4) extensive interviews, conversations, and thorough peer review by experts from utility companies, including historic data from past earthquakes and utility emergency response plans for future events (Çağnan et al. 2006; Xu et al. 2007; Tabucchi et al. 2010; Davis et al. 2012; Davis 2014); and (5) expert opinion survey data (FEMA 2010) and published literature to identify causal and logical relationships among restoration indicators (De Iuliis et al. 2021a, b).

Energy Systems

Although significant uncertainty exists in parameters related to the recovery process (financing planning, availability of human resources, regulatory and economic processes), seismic intensity and infrastructure characteristics have been found to be the two most important parameters affecting the restoration of electric power systems (De Iuliis et al. 2021a). For the restoration of multiple lifelines, electric power systems are the first to recover, followed by telecommunication systems, water systems, and natural gas systems due to the dependency of water and gas systems on electric power systems (Kammouh et al. 2018; De Iuliis et al. 2021a). Natural gas systems are generally the last to be completely restored due to the mandatory testing and investigations required to ensure safety after a hazardous event (Cimellaro et al. 2015; Kammouh et al. 2018). Fig. 5(a) presents an example empirical restoration and recovery model for natural gas systems as a function of increasing earthquake magnitude based on recovery data of lifelines gathered for 32 earthquakes (Kammouh et al. 2018). Fig. 5(b) presents an analytical restoration model for natural gas systems for two networks, one without automatic shutoff valves with the bridge-supporting pipelines failing and the other with automatic shutoff values as a retrofitting measure, which significantly improved the functionality of the latter network compared to the former (Cimellaro et al. 2015).

Water and Wastewater Systems

Functional restoration of water and wastewater systems has often been modeled as connectivity based, as measured in terms of the number of active network connections, population served, or pipe length in service (Porter 2016; Porter et al. 2017; Liu et al. 2017). However, network connectivity alone is often not a sufficient indicator of the performance of water and wastewater systems (Davis 2014) and can significantly overestimate the actual state of the wider system when reported alone without the level of service (Zorn and Shamseldin 2017). More holistic system-wide recovery models based on the restoration of specific service categories, like water delivery, quality, quantity, fire protection, or functionality (Davis et al. 2012; Davis 2014), and level of service (e.g., normal, restricted, no service) have also been proposed (Zorn and Shamseldin 2017). Fig. 5(c) shows the continuous restoration models for water treatment plants proposed in FEMA (2010) on the basis of expert opinion. Fig. 5(d) presents water system restoration models, in which the restoration of five service categories of water system and their interaction was explicitly modeled (Davis 2014) and able to represent the complex interactions of different service categories and their impact on overall water system resilience.

Multihazard, Interdependencies, and Cascading Infrastructure Failure

Existing multihazard fragility functions for energy, water, and wastewater systems have mostly focused on ground shaking and

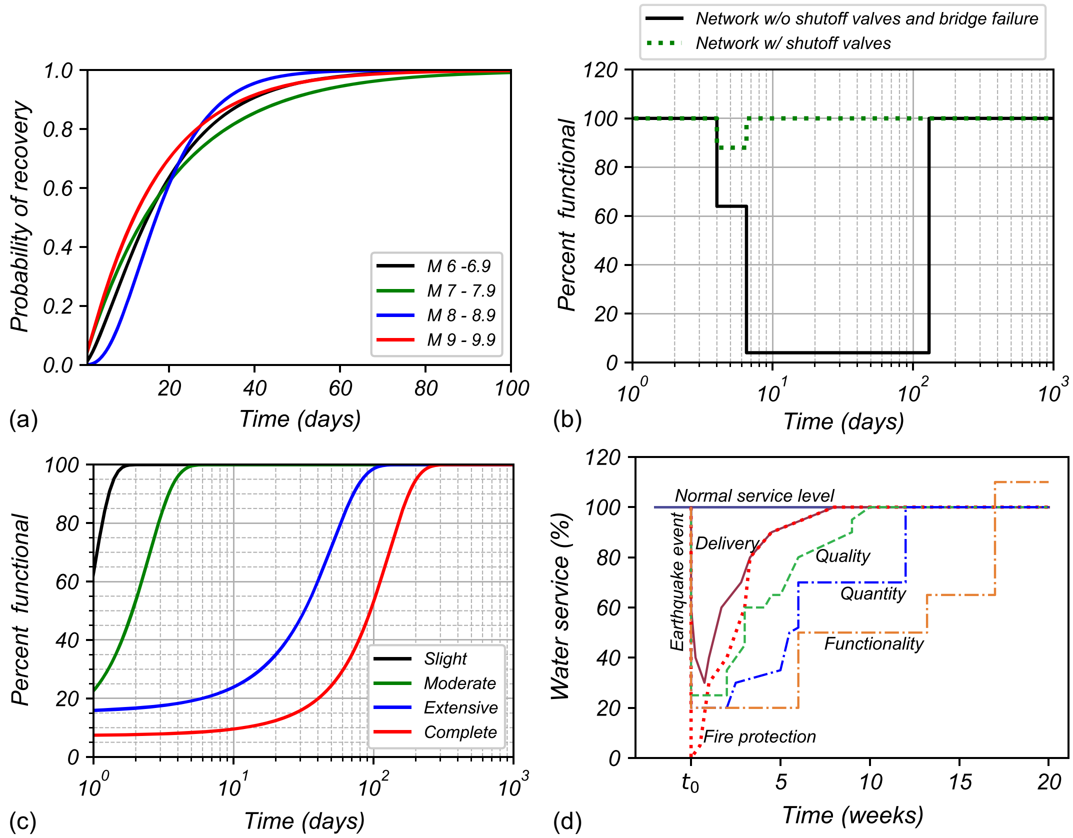

Fig. 5. Example restoration and recovery models for natural gas systems: (a) as a function of probability of recovery for different magnitude earthquakes (data from Kammouh et al. 2018); and (b) in terms of % functional of the network for networks with and without preventive system (automatic shutoff valves) and bridge failure (data from Cimellaro et al. 2015). Restoration models for: (c) water treatment plants (data from FEMA 2010); and (d) water system in terms of various service categories (data from Davis 2014).

ground failure [e.g., for natural gas pipelines (Farahani et al. 2020), water pipelines (Eskandari et al. 2017)], ground shaking, ground failure, and fire following earthquake [e.g., for natural gas pipelines (Omidvar and Kivi 2016)], ground shaking, ground deformation, and aging [e.g., for water pipelines (Farahmandfar and Piratla 2017)], and earthquake-hurricane wind [e.g., for electric power transmission systems (Reed 2009; Salman and Li 2018; Jeddi et al. 2022)]. Seismic-induced rockfall, riverine flooding (FEMA 2009), fires (Parsons 1976), coastal flooding (FEMA 2013; Khakzad and Van Gelder 2017), and tsunamis (Alam et al. 2018, 2019; Alam 2019; Attary et al. 2017) can also be important multihazards, and there is currently a lack of fragility surfaces for these multihazard scenarios for energy, water, and wastewater systems.

Cascading infrastructure failures can also occur between many of the aforementioned infrastructure classes, e.g., when one failure triggers failures in other infrastructure components or systems. Dependencies (one-way) and interdependencies (one-way, reciprocal, or multiple level) between infrastructure systems are paramount to restoring infrastructure services in an appropriate sequence and to avoid cascading delays in the restoration of critical services. The NIST Community Resilience Planning Guide (CRPG) (NIST CRPG 2016) classifies the dependencies and interdependencies of buildings and infrastructure systems in a community as internal and external dependencies [e.g., as documented by Pederson et al. (2006) for emergency services], space dependencies, and source dependencies. An example of interdependencies for water systems and other infrastructure is shown in Table 9 of the online repository (Alam et al. 2022b). The City of San Francisco's Lifeline Council identified potential dependencies of other infrastructure classes following a scenario M7.9 earthquake on the San Andreas Fault (CCSFLC 2014).

Summary and Future Research Needs

A comprehensive review of the state-of-the-art seismic fragility functions and recovery models developed during the last three decades (1990–2021) for energy systems (power, liquid fuel, and natural gas), water, and wastewater systems was performed for the future application of fragility models of lifelines in the regional scale risk and resiliency assessment of communities. This review focused on fragility and recovery model parameters and summarized methods and validation used in the development of the models. Expert elicitation from utility providers was used to identify important fragility function attributes (such as failure mechanisms, damage measure, intensity measure). In addition, the collected fragility functions were compiled in an open-source database (Alam et al. 2021, 2022a). Considering this review, gaps and recommendations include the following:

- For electric power systems, fragility functions are lacking for transmission lines and transmission towers for ground shaking, landslide, and liquefaction. For example, high-voltage transmission towers and transmission lines located at riverbanks and hilly regions should be prioritized for fragility function development because these can be susceptible to liquefaction, landslides, and lateral spreading and may block river channels and/or roadways upon their failure.

- For liquid fuel systems, fragility functions are lacking for refineries and fuel pipelines. It is a widespread practice to use identical fragility functions for water and liquid fuel system pipelines. However, liquid fuel pipelines operate under different flow pressures and carry fluid of different viscosities and temperatures. Moreover, many of the liquid fuel pipelines in certain regions of the US and worldwide date from the 1960s and, thus, were designed prior to the development of modern seismic provisions. Fragility functions for liquid fuel pipelines still need to be developed, especially considering the importance of fuel pipelines in many states and national fuel supply ensuring that the CEI hubs remain functional during and in the aftermath of an earthquake event. Many of the CEI hubs are located near or on waterways that typically include soils susceptible to liquefaction and lateral spreading, and care should be exercised to account for these hazards and potential consequence of failure of pipelines on the environment and biodiversity while developing fragility function.
- For natural gas systems, fragility functions are lacking for subsurface storage facilities, compressor stations, and gas pipelines. Similar to liquid fuel pipelines, many of the natural gas pipelines are based on those for water pipelines. Thus, fragility functions for natural gas pipelines and compressor stations also need to be developed considering liquefaction and lateral spreading hazards. Fragility functions for LNG tanks are also lacking in the literature.
- For water and wastewater systems, there is a lack of fragility functions for the control systems of water systems and for the treatment plants and lift stations of wastewater systems. Treatment plants built on liquefiable soils without special designs are likely to suffer catastrophic damage due to foundation failures, as has been observed in 2010–2011 Canterbury, New Zealand, earthquake sequence (Eidinger et al. 2010; Giovinazzi et al. 2011). Moreover, the failure of lift stations located in liquefiable areas can affect public health for gravity-fed sewers. Recently, different water districts in Oregon have developed their own seismic design and assessment guidelines on the basis of site-specific hazard analysis in efforts to promote seismic resiliency [e.g., for water systems (InfraTerra 2017) and wastewater systems (BES 2018)]. However, future studies should be conducted to develop fragility functions for these facilities.
- Interdependencies of co-located infrastructure for bridges/roadways and utility lines (e.g., electrical, water and wastewater pipelines, liquid fuel/natural gas pipelines with bridges) need to be considered and are currently lacking in the literature.

Use of appropriate verification and validation (V&V) methods in the development of fragility functions and recovery models can ensure reduced model bias and improved reliability. Limited V&V information is available for many of the existing fragility functions and recovery models, affecting confidence of their quality and is often left to the discretion of the user for their potential applications. To enhance the reliability of these models, future studies should consider rigorous V&V as a core component in the development of fragility functions and recovery models. In this regard, high-quality damage data of lifeline infrastructure, which is scarce in many instances, gathered through real-time monitoring [e.g., smart pipelines (Simpson et al. 2015; PEER 2019)] and robust field measurement techniques [e.g., LiDAR, unmanned aerial systems (UAS), total station] will play a vital role for realistic damage quantification to validate fragility functions.

Data Availability Statement

Supplemental materials associated with this paper can be found in the digital appendix in DesignSafe-CI (Alam et al. 2022b). All other data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request, except for the studies conducted by different utility companies (e.g., InfraTerra 2017; BES 2018; SEFT 2018), which are proprietary in nature.

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